N66-18361

(ACCESSION NUMBER)	(THRU)
27	1
(PAGES)	(CODE)
TMX 56171	30
(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)

FACILITY FORM 602

PRESUPERNOVA EVOLUTION (NEUTRINO STARS)

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Received ____________________

[redacted]

GPO PRICE $ ____________

CFSTI PRICE(S) $ ____________

Hard copy (HC) 2.00

Microfiche (MF) .50

ff 653 July 65

ABSTRACT

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The later stages of stellar evolution, when the internal temperature is above 10^9 °K, are affected by neutrino processes. Under these conditions the neutrino emission occurs at a rate higher than the photon emission rate. It is found that the homology relation (Density) $\sim$ (Temperature)^3 breaks down completely and that in general the density rises much faster than the third power of temperature. In regions where nuclear burning commences (C^{12} - O^{16} or O^{16} - O^{16} reactions) the interior stellar structure is determined by the condition: (Nuclear Energy Production Rate) + (Neutrino Energy Dissipation Rate) = 0. Such curves have negative power dependence on temperature ($\rho \sim T^{-12}$) or are isothermal depending on the density. The rapid removal of energy from the core of the star results in a short time scale for these stages and the star continues to contract. The stars evolve (independently of their mass) to a very high central density ($\sim 10^{9-10}$ g/cm^3) at a rather low central temperature ($\sim$ 3-4 x 10^9 °K). It may be concluded that the star does not reach the <u>full</u> iron-helium phase cha as previously suggested (Fowler and Hoyle, 1964). Stellar collapse will be induced at this density and temperature either by β-transition or by a small amount of iron-helium transition.

author

INTRODUCTION

The problem of supernova collapse has acquired considerable interest in recent years, in connection with general relativity and element synthesis. In most literature conclusions are based on extremely simplified structures for presupernova stars. The most often quoted presupernova model is a polytropic model of polytropic index $n = 3$, and the subsequent contraction to a dynamical collapse is assumed to be homologous. In the later stages of stellar evolution when the temperature exceeds 10^9 $^{\circ}$K, it has been shown that neutrino processes will dissipate stellar energy rapidly, with a time scale for evolution of the order of a few thousand years or less, this time scale is shorter than the time scale for redistribution of radiation energy in the star. On the other hand in the homologous contraction hypothesis it is implicitly assumed that the time scale for energy redistribution is much shorter than the time scale for stellar evolution. Therefore, homologous contraction hypothesis cannot be applied to stellar evolution problems when $T \gtrsim 10^9$ $^{\circ}$K. It is the purpose of this paper to discuss the structure of presupernova stars without assuming the validity of the homologous contraction hypothesis.

THE BASIC EQUATIONS

The stellar structure equations are

$$\frac{dP}{dr} = -\rho \frac{GM_r}{r^2} \tag{1}$$

$$\frac{dM_r}{dr} = 4\pi r^2 \rho \tag{2}$$

$$\frac{dL_r}{dr} = 4\pi r^2 \rho \mathcal{E} \tag{3}$$

$$\left.\begin{aligned} \frac{dT}{dr} &= -\frac{3}{4ac} \frac{\kappa \rho}{T^3} \frac{L_r}{4\pi r^2} \quad \text{(radiative)} \\ \frac{dT}{dr} &= \left(1 - \frac{1}{\gamma}\right) \frac{T}{P} \frac{dP}{dr} \quad \text{(convective)} \end{aligned}\right\} \tag{4}$$

The notations used are the standard notations (e.g. those used by Schwarzschild (1958)).

We now discuss the influence of neutrino processes on stellar structure. The cross section for interaction of neutrinos with matter is around 10^{-44} cm^2, in contrast to that for photons which is around $10^{-20} \rightarrow 10^{-25}$ cm^2. The mean free path for neutrinos in lead is around one light year! Only under extreme density conditions ($\rho \gtrsim 10^{11}$ g/cm^3) must one consider the absorption of neutrinos by stellar matter (Chiu 1964). Neutrino opacities in dense matter have been considered by Bahcall (1964) and Bahcall and Frautschi (1964). Since the star does not absorb neutrinos, the only place they can enter the stellar structure equations is through equation (3) which describes the energy balance of the star. In equation (3) $\mathcal{E}$ is the energy production term, and we have

$$\varepsilon = \varepsilon_{gr} + \varepsilon_n + (dU/dt) \;, \tag{5}$$

where ε_{gr} is the rate of gravitational energy release (in ergs/g-sec), ε_n the rate of nuclear energy release, and (dU/dt) is the rate energy is dissipated by neutrino emission.

We shall now estimate the rate of photon energy transfer and the rate of neutrino emission inside a star. The photon opacity $\varkappa_{ph}$ of stellar matter is always greater than $\varkappa_e = 0.19$ cm^2/g (the opacity for electron scattering). The mean free path of photons is roughly $(1/\varkappa_e)$ in g/cm^2, and hence is always shorter than 5 g/cm^2. The luminosity of a star apart from a numerical factor which is not very different from unity is roughly

$$L \approx \frac{\text{(Photon Energy Content of the Star)}}{(R/c)\cdot(R/\lambda)} \;, \tag{6}$$

where R is the radius of the star and c is the velocity of light, and λ is the photon mean free path (in cm). The relaxation time for a star to be cooled by photon emission τ_{ph} is therefore

$$\tau_{ph} = \frac{\text{(Photon Energy Content of the Star)}}{(L)} = \frac{R^2}{c\lambda} \;. \tag{7}$$

Using a simple model in which the temperature T and the radius R are related by the following condition (which is derivable from the virial theorem)

$$-\text{(Gravitational Energy)} = \tfrac{1}{2}(GM^2/R) = (3/2)R_g T M$$

$$= \text{(Thermal Energy)}, \tag{8}$$

we find

$$\tau_{ph} = 2\times10^{11}\, T_9 \quad \text{sec} . \tag{9}$$

The corresponding relaxation time via pair annihilation neutrino emission τ_ν is

$$\tau_\nu = \frac{\mathcal{E}}{-(dU/dt)} = 1.5 \times 10^4 \exp[11.9/T_9] T_9 (\odot/M)^2, (T_9 << 6). \tag{10}$$

At $T_9 = 1$, $\tau_\nu = 2\times10^7$ sec and $\tau_{ph} = 2\times10^{11}$ sec. Hence we can conclude that at $T_9 \gtrsim 1$ the photon energy transport process cannot be important in the center of stars.

Soon after the temperature exceeds $\sim 10^9$ °K the rate of energy dissipation by neutrinos will dominate over the photon processes. Thus there exist only narrow temperature-density regions where one must consider both photon and neutrino processes simultaneously. Outside this region one can either completely neglect the photon energy transfer process (except for luminosity calculation) or completely neglect the neutrino processes. We shall define a star to be a photon star if the major part of the energy loss of the star is through surface emission, and a neutrino star if the major part of the energy loss is through neutrino emission.

The idea of a neutrino star is only an abstraction: In real stars the surface temperature is in between 10^3-10^5 °K, thus in the outer region of a star photon processes must dominate. However, the neutrino active core will evolve rapidly before the outer region can effectively affect the core's structure (e.g. by the addition of mass to the core, or the addition or removal of energy from the core). Thus, the concept of a neutrino star will be helpful in obtaining the evolutionary properties of a star in its later stages.

Since we neglect L as compared with $-\int (dU/dt)\, dM_r$ (where the integration extends over the whole star) we can also assert that in the neutrino active region $(dL/dM) \ll -(dU/dt)$. In the first approximation to equation (3) we replace (dL/dM) by zero. Equation (3) then becomes

$$\mathcal{E} = -T(dS/dt)_M + \mathcal{E}_n + (dU/dt) = 0, \tag{11}$$

where S is the entropy per unit mass.* Partial differentiation of S with respect to t is taken at a shell of constant mass M_r. (Convection cannot occur in neutrino stars, because the temperature gradient never exceeds the adiabatic temperature gradient.)

Effectively equation (4) may be ignored in calculating the mechanical structure of the neutrino star in regions where neutrino emission is strong. That is to say, the structure of the star is not effected by the inclusion of equation (4). Once the structure is obtained one can calculate L from equation (4). The equations for the stellar structure of a neutrino star are given by equations (1) and (2) and equation (11). It can be shown that if $\rho(r)$ and $T(r)$ are given at $t = t_o$, the structure of the star at a later time is uniquely determined. The proof is quite elementary, though tedious.

*It can easily be demonstrated that $\mathcal{E}_{gr} = -T(dS/dt)$.

EVOLUTION OF A NEUTRINO STAR WITHOUT NUCLEAR ENERGY GENERATION

The energy sources of stars are either gravitational or nuclear in origin. Nuclear reactions occur at well defined temperatures, and when nuclear energy is not available the star must contract to supply the energy lost via neutrino emission or photon emission.

At lower temperatures ($T \lesssim 10^7$ ^oK) it was found that stars contract in a simple fashion. Under the assumption that the temperature and density relations of a star are such that one can write

$$P = K\rho^{(1+(1/n))} , \tag{12}$$

where K is a constant depending on the mass of the star and n is the polytropic index, one can simplify equations (1) and (2) by the following substitutions

$$\rho = \lambda\theta^n , \tag{13}$$

$$r = r_o\xi , \tag{14}$$

where r_o and λ are also constants. The resulting equation is the Lane-Emden equation

$$\frac{1}{\xi^2}\frac{d}{d\xi}(\xi^2\frac{d\theta}{d\xi}) = - \theta^n . \tag{15}$$

However, a family of solutions is derivalbe from one existing solution for equation (15): If $\theta(\xi)$ is a solution, then it can be shown that

$$A^{(2/(n-1))}\theta(A\xi) \tag{16}$$

is also a solution (this is known as the homology hypothesis).

Further, when one applies this hypothesis to evolving stars, one finds that inside a star, at a given shell mass M_r, the relation of the density ρ and the temperature T in the course of time is

$$\rho \propto T^3 \quad (17)$$

Hence, if the polytropic index n is a constant in the course of stellar evolution, then equation (17) is valid and the structure of a star can be characterized by the function $\theta(\xi)$; the evolution will introduce only a change in the scale. (For proof, see for example, Eddington (1930) or Fowler and Hoyle (1964).)

This simple result works remarkably well for many types of stars. One implicit assumption involved in the application of the homology hypothesis to stellar evolution (this is called the homologous contraction hypothesis) is the following: Energy can br redistributed inside stars at a rate much faster than it can be produced by gravitational contraction.

Fowler and Hoyle (1960, 1964) have applied the homologous contaction hypothesis to stars in their late evolutionary stages. Under certain assumptions they concluded that a star of mass around 30 $M_\odot$ will collapse when the center reaches a temperature of $\sim 6\times10^9$ °K and a density of 2×10^7 g/cm^3. A separate estimate by Chiu (1964) and by Chiu and Fuller (1962) using a similar hypothesis showed that long before this temperature and density is reached a collapse will take place via neutrino processes.

We now examine whether the homologous contraction hypothesis can be applied to neutrino stars. In the absence of $\mathcal{E}_n$ equation (11) becomes

$$T(dS/dt)_M = (dU/dt) \quad (< 0)$$

$$= -(\epsilon_{\nu_o}/\rho)T^K \quad \text{for nondegenerate stars} \qquad (18)$$

where $T_9 \gtrsim 3$, $\epsilon_{\nu_o} = 4.3 \times 10^{15}$, and $K = 9$. For a nondegenerate gas, S is given by the following equation

$$S = R_g \ln(T^{\alpha}\rho^{-1}) + \text{Constant} \quad , \qquad (19)$$

where α is a slowly varying constant; $\alpha = 1.5$ for nonrelativistic matter ($T_9 << 1$) and $\alpha = 3$ for relativistic matter ($T_9 \approx 6$); at $T_9 = 2$, $\alpha \approx 2.7$.

We now assume that at each shell mass ρ and T evolve according to the following relation

$$(\rho/\rho_o) = (T/T_o)^{\beta} \quad , \qquad (20)$$

where ρ_o, T_o, and β are constants. The homologous contraction hypothesis will require that $\beta = 3$ throughout the star. Substituting equations (19) and (20) into equation (18) one obtains

$$(dT_9/dt) = \gamma T_9^{K-\beta} \quad , \qquad (21)$$

where

$$\gamma = \frac{\epsilon_{\nu_o} T_o^{\beta}}{\rho_o R_g(\beta-\alpha)} \quad . \qquad (22)$$

Equation (21) can be solved exactly to give

$$T_9 = (T_9^{o})/(1 - (t/t_o))^{[1/(K-\beta-1)]} \quad , \qquad (23)$$

where

$$t_o = \left(\frac{1}{K-\beta-1}\right)\cdot\left(\frac{\beta-\alpha}{\alpha}\right)\tau_\nu \qquad . \qquad (24)$$

τ_ν is the relaxation time for the neutrino energy loss (equation (10)). Thus for a homologously contracting neutrino star, a collapse occurs at a time $t = t_o$. If we use $\beta = 3$, $K = 9$, $\alpha = 2.7$, then $t_o = (1/45)\tau_\nu$. The free fall time for a 10 $M_\odot$ star is reached $T_9 \sim 3$ (Chiu 1964).

The collapse can be delayed to higher temperatures if the value of β is close to $K - 1 = 8$. One exact calculation on the evolution of neutrino stars was recently done by Chiu and Salpeter (1965). This calculation confirms our guess that the value of β is close to 8 for the central region of the star. The stellar mass is chosen to be 10 $M_\odot$ and the initial configuration is chosen to be that of a polytrope of $n = 1.5(\rho \propto T^{3/2})$. No approximation was made to the equation of state which included contributions from electrons and positrons, radiation, and heavy nuclei (iron). In the log ρ - log T plane the structure of the star is represented initially be a straight line of slope 1.5. If the star evolves homologously, then this line will be displaced without distortion along a line of slope 3 (Figure 1). The actual evolution of the star is very complicated, as indicated in Figure 2. Since the neutrino energy loss rate at high densities is from the plasma neutrino process, the rate increases with increasing density, and a positive temperature gradient develops throughout the inner 1/3 of the mass of the star.

In this model we have demonstrated that if nuclear reactions are neglected then the homologous contraction hypothesis cannot be applied to neutrino stars, for central conditions evolve according to $\rho \sim T^n$ where $6 \le n \le 9$.

EVOLUTION OF NEUTRINO STARS WITH NUCLEAR REACTIONS

The time scale τ_ν for a star with no energy source other than the gravitational energy to remain at a temperature T is given by

$$\tau_\nu \approx E/(-dU/dT) \qquad (25)$$

In reality the time scale is shortened by a factor of around 4. On the other hand nuclear energy (from $O^{16} - O^{16}$ reaction and the $C^{12} - O^{16}$ reaction) is fairly abundant. The time scale τ_n for nuclear burning at a temperature such that

$$\varepsilon_n + (dU/dt) = 0 \qquad (26)$$

is several times (~ 10) greater than τ_ν, but still much less than the photon diffusion time. Because nuclear reactions have much steeper temperature dependence ($\sim T^{30}$) than that of the neutrino rate ($\sim T^9$) a negligible amount of nuclear fuel will be consumed below the temperature defined by equation (26).

Once nuclear burning starts, in that part of the star, gravitational contraction can take place only along curves given by the condition

$$\mathcal{E}_{gr} + \mathcal{E}_n + (dU/dt) = 0 \quad . \tag{27}$$

Since, in $\mathcal{E}_{gr}$, ρ and T appear in logarithms (equation (19)), the condition

$$\left(\frac{dU}{d\xi}\right) + \mathcal{E}_n \cong (\text{Constant})\cdot T \quad , \tag{28}$$

determines the temperature and density relation according to which the star can evolve.

For the $C^{12} - O^{16}$ and $O^{16} - O^{16}$ nuclear reactions, Fowler and Hoyle (1964) have given the following rates:*

$$\log \mathcal{E}_{12-16} = 49.7 + \log_{10} \rho x_{16} x_{12} - (2/3)\log_{10} T_9$$

$$- (46.30/T_9^{1/3})(1 + 0.080T_9)^{1/3} \, , \tag{29}$$

$$\log \mathcal{E}_{16-16} = 55.7 + \log_{10} \rho x_{16} x_{16} - (2.3)\log_{10} T_9$$

$$- (59.04/T_9^{1/3})(1 + 0.080T_9)^{1/3} \, , \tag{30}$$

where x_a is the concentration of element a. At $\rho \sim 10^6$ g/cm^3 we find that the temperature defined by equation (26) is roughly $T_9 = 2.45$ for the $O^{16} - O^{16}$ reaction and $T_9 = 1.25$ for the $O^{16} - C^{12}$ reaction; at these two temperatures one can approximate $\mathcal{E}_{16-16}$ and $\mathcal{E}_{12-16}$ by simpler formulae

$$\mathcal{E}_{16-16} = 8\text{x}10^{-6} \rho T_9^{33} \quad \text{ergs/g-sec} \quad , \tag{31}$$

$$\mathcal{E}_{12-16} = 1.32\text{x}10^{9} \rho T_9^{31.8} \text{ ergs/g-sec} \; . \tag{32}$$

Equation (28) thus gives

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*At present calculations by Salpeter and Deinzer (1964), Stothers (1964) and Divine (1964) seem to indicate that $C^{12} - C^{12}$ and $C^{12} - O^{16}$ reactions do not take place, since carbon will not be produced by helium burning in massive stars.

$$8\times10^{-6}\rho T_9^{33} + (4.3\times10^{15}/\rho)T_9^{9} = (\text{Constant})\cdot T$$

$$(O^{16} - O^{16}\ \text{Burning}), \qquad (33)$$

$$1.32\times10^{3}\rho T_9^{31.8} + (4.8\times10^{18}/\rho)T_9^{3}\exp[-2(T_O/T_9)]$$

$$= (\text{Constant})\cdot T \qquad (C^{12} - O^{16}\ \text{Burning}). \qquad (34)$$

In the log ρ - log T plane equations (33) and (34) are lines of negative slope, which we shall call the n-ν curves. The particular curves with the constant replaced by zero will be called the n-ν-zero curves. We have plotted the n-ν-zero curves for O^{16} - O^{16} burning and C^{12} - O^{16} burning (Figure 3).

To what degree can the structure of a neutrino star in the nuclear burning stage itself deviate from the n-ν-zero curves? The nuclear energy rate has a very sharp temperature dependence. A deviation in temperature T by a factor of 4 % from the curve will cause nuclear energy production rates to vary by more than a factor of 3 while the neutrino rate only varies from by about 40 % ! Imagine that the star is on the lower temperature side; then a gravitational contraction will raise the temperature of the star until nuclear energy production takes over the gravitational energy production and in this part of the star contraction will start. If the star is on the higher temperature side, then the excess energy produced by nuclear reactions will expand the star until the temperature is low enough so that an energy balance is reached. Thus the star is always pushed toward the n-ν-zero line.

Because of the extremely rapid cooling by neutrino emission, there is a positive temperature gradient in the core of the star and the maximum temperature, and so nuclear burning, occurs in a shell surrounding the core. Thus the core continues to collapse with $\rho \sim T^8$ until it reaches the n-ν-zero line, and nuclear burning begins. The nuclear burning shell evolves along the n-ν-zero line. And, because the time scale of evolution is much shorter than the photon diffusion time, the energy from the nuclear burning is not transferred to the envelope, which also continues to contract. Thus the structure of the star approaches the n-ν-zero line. When the central density approaches 4×10^7 g/cm^3 for $O^{16} - O^{16}$ burning or 4×10^6 g/cm^3 for $C^{12} - O^{16}$ burning, the plasma neutrino process becomes important. The plasma neutrino loss rate Q_t can be approximated to an accuracy of better than 50 % at $x \leq 1$ by

$$\log Q_t = 6.04 + 3 \log T_9 + \log \rho_6, \qquad (35)$$

where if $\rho_6 >> 1$, x is given by

$$x = 0.237(1 + 0.6413\rho_6^{2/3})^{-\frac{1}{4}} \rho_6^{\frac{1}{2}} T_9^{-1} \qquad (36)$$

The n-ν-zero curve becomes a vertical line and the temperature is independent of the density and is a constant. For the $O^{16} - O^{16}$ burning process we have

$$\log T_9 = 0.138 - (1/30) \log(x_a x_b), \quad T_9 \sim 1.38, \qquad (37)$$

$$\text{Time scale} \sim 10^8 \text{ sec} \qquad (38)$$

Thus during nuclear burning the core evolves according to the condition $\mathcal{E}_n + (dU/dt) = 0$ and a dense core is formed independent of the mass of the star. Only an exact calculation will tell us what the final density will be. Until the nuclear fuel is completely consumed the temperature of the star cannot increase.

The time scales for evolution via neutrino emission in a realistic star are indicated on Figure 3. These differ drastically from those predicted on the basis of simple polytropes. A neutrino star, it seems, evolves quickly (in 10^7 sec) at a temperature of around 1.2×10^9 ^oK ($C^{12} - O^{16}$ burning) or 2.5×10^9 ^oK ($O^{16} - O^{16}$ burning), its density increasing rapidly. The time scale then becomes longer ($\sim 10^8 - 10^9$ sec for $O^{16} - O^{16}$ burning, and $\sim 10^{11}$ sec for $C^{12} - O^{16}$ burning). It is not known if the density will reach a value of $\sim 10^{10}$ g/cm^3.

At densities around 10^9 g/cm^3 β-transitions and pycnonuclear reactions (Cameron 1959) will cause elements to approach an equilibrium state quickly. Tsuruta (1964) has considered the equilibrium of elements in this density-temperatrue regime. This approach to nuclear equilibrium or, at higher density the formation of neutrons, or even a small amount of Fe disintegrates to He, may be the trigger of the supernova collapse.

On the basis of evolutionary properties of photon stars Burbidge, Burbidge, Fowler, and Hoyle (1957), and later in a more elaborate version Fowler and Hoyle (1960, 1964), have argued that the transition from iron to helium at a density of around 10^7 g/cm^3 and a temperature of 7×10^9 $^{\circ}$K is sufficient to cause a star of mass around 30 $M_{\odot}$ to collapse. However, it seems that this density and temperature cannot be reached simultaneously in neutrino stars; the structure of neutrino stars is so drastically different from that of photon stars that their argument is invalidated. It is possible that the final collapse state will be at a very high density ($\sim 10^{9-10}$ g/cm^3) and at a much lower temperature ($\sim$ 3-4x10^9 $^{\circ}$K)

CONCLUSION

We have found that the classical homology hypothesis $\rho \sim T^3$ is completely inapplicable to the evolution of stars whose temperatures are over 10^9 $^{\circ}$K, where neutrino processes dominate over photon processes - such stars we have called neutrino stars. Instead, neutrino stars during gravitational contraction evolve with $\rho_c \sim T_c^{\,8}$, while during nuclear burning they evolve along the n-ν-zero curves which lead any star (independent of its mass) to a region of very high density. After the exhaustion of nuclear fuel the central temperature will increase again. The final collapse of all neutrino stars into supernova will probably occur at a density of around 10^{9-10} g/cm^3 and at a temperature of around 3-4 x 10^9 $^{\circ}$K. The mechanism for collapse is thought to be the approach to equilibrium of elements (at high density) via β-transitions or pycnonuclear reactions.

We have not included the electron conduction opacity. At $\rho \sim 10^9$ g/cm^3 the opacity due to electron conduction is exceedingly small, the positive temperature gradient may thus be replaced by an isothermal gas sphere.

ACKNOWLEDGEMENT

I would like to thank Dr. L. Adler for his competent programming work on numerical integrations, Dr. A.G.W. Cameron, Dr. W.A. Fowler, and Dr. E. E. Salpeter for discussions and the the hospitality of the Kellogg Radiation Laboratory of the California Institute of Technology where part of this work was carried out.

REFERENCES

Bahcall, J. N. 1964, Phys. Rev. 136, B1164.

Bahcall, J. N. and Frautschi, S. 1964, Phys. Rev. 136, B1547.

Burbidge, E.M. Burbidge, G.R., Fowler, W.A., and Hoyle, F. 1957, Rev. Mod. Phys. 29, 547.

Cameron, A.G.W. 1959, Ap. J. 130, 884.

Chiu, H.-Y. 1964, Ann. Phys. 26, 364.

Chiu, H.-Y. and Fuller, R. 1962, NASA Goddard Institute for Space Studies preprint.

Chiu, H.-Y. and Salpeter, E.E. 1965, To be published.

Divine, T. N. 1965, Ph.D. thesis, California Institute of Technology.

Eddington, A.S. 1930, Internal Constitution of the Stars (Cambridge: Cambridge University Press).

Fowler, W.A. and Hoyle, F. 1960, Ap. J. 132, 565.

Fowler, W.A. and Hoyle, F. 1964, Ap. J. Supplement 9, 201.

Salpeter, E.E. and Deinzer, W. 1964, Ap. J. 140, 499.

Schwarzschild, M. 1958, The Structure and Evolution of the Stars (Princeton, New Jersey: Princeton University Press), p.96.

Stothers, R. 1964, Private Communication.

Tsuruta, S. 1964, Ph.D. thesis, Columbia University.

LEGENDS

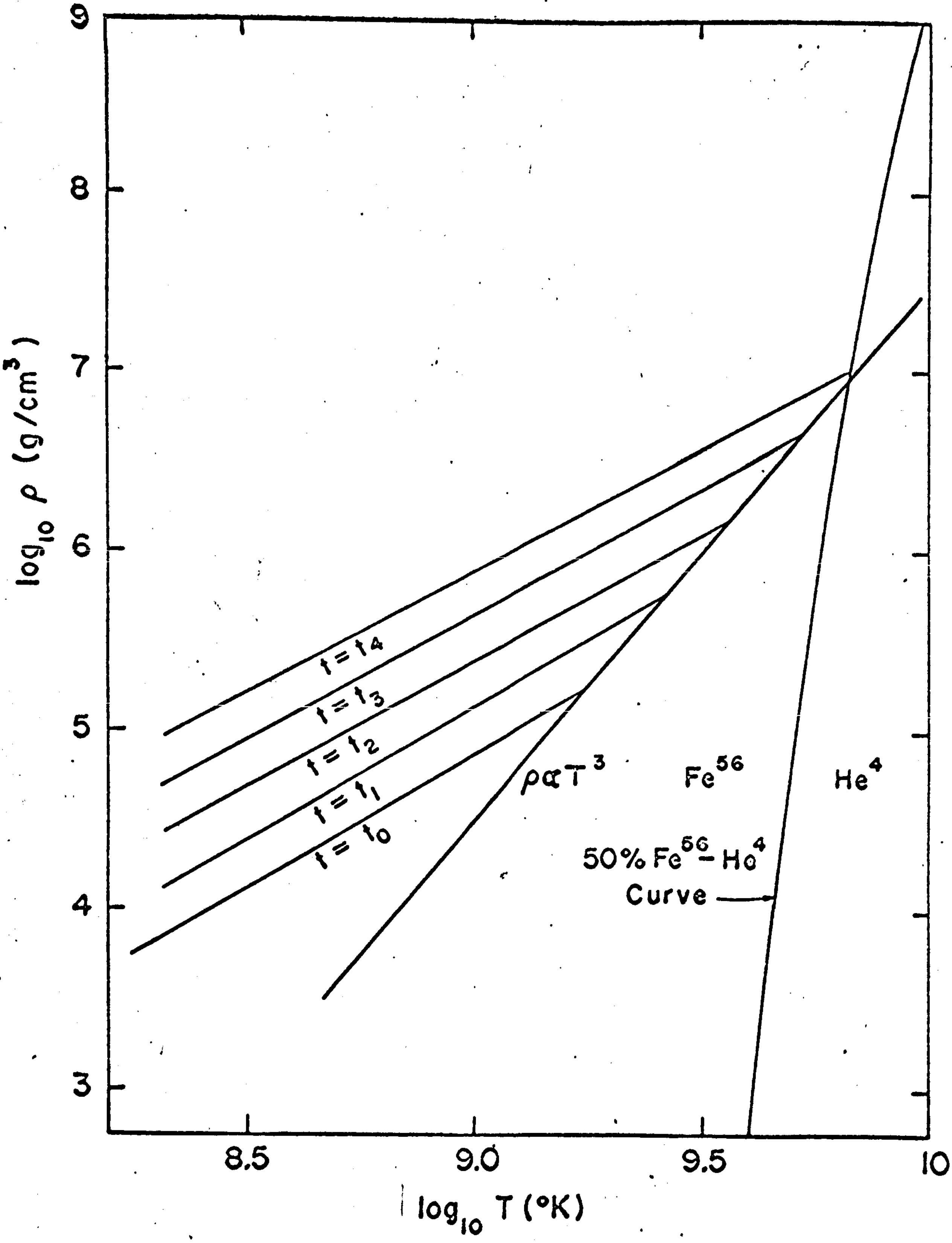
Figure 1. The evolution of homologously contracting polytrope model stars with a polytropic index n = 1.5. All parts of the star evolve according to the law $\rho \propto T^3$. For a 10 $M_\odot$ star the center will reach the Fe^{56} - He^4 region at a density $\rho \sim 10^7$ and $T \sim 7 \times 10^9$ °K. While the concept of homologous contractions works reasonably well for photon stars, it breaks down completely for neutrino stars as in Figure 2.

Figure 2. The evolution of neutrino stars. The structures at various times are shown. The highest density point on each curve is the center of the star. Although t is given to 7 decimal places only the time differences between stages are useful numbers. The evolution is very different from that for a photon star (Figure 1). In this model the collapse condition is obtained at $\rho \sim 10^9$ g/cm^3 while the star is still composed of iron. This model demonstrates the complete break down of the concept of homologous contraction in neutrino stars.

Figure 3. n-ν-zero curves for O^{16} - C^{12} and O^{16} - O^{16} reactions. x_a is the concentration of the element a and a curve with $x_a = 0.2$ is also shown for comparison. Along the n-ν-zero curves the nuclear energy release rate is equal to the neutrino rate. The bending at higher densities occurs because the plasma neutrino rate becomes important and the plasma neutrino rate has a different density -

temperature dependence from that of annihilation neutrinos. Numbers on the graphs refer to ($\log \tau_n - \log x_a$) (τ_n is the time scale in seconds for nuclear burning at that point). The 50 % $Fe^{50} - He^4$ curve is also shown. Dotted line (- - - - - -) is the evolution track of a model star of 30 $M_\odot$ studied by Fowler and Hoyle (1964). Actual stars must evolve along the n-ν-zero lines. The hyphenated line (- — - — - — - —) separates regions in which plasma or annihilation neutrino processes dominate as indicated.

Figure 1.



9
8
7
6
5
4
3
log10 ρ (g/cm3)
8.5
9.0
9.5
10
log10 T (°K)
t = t4
t = t3
t = t2
t = t1
t = t0
ρ∝T 3
Fe56
He4
50% Fe56 - He4
Curve

Figure 2.

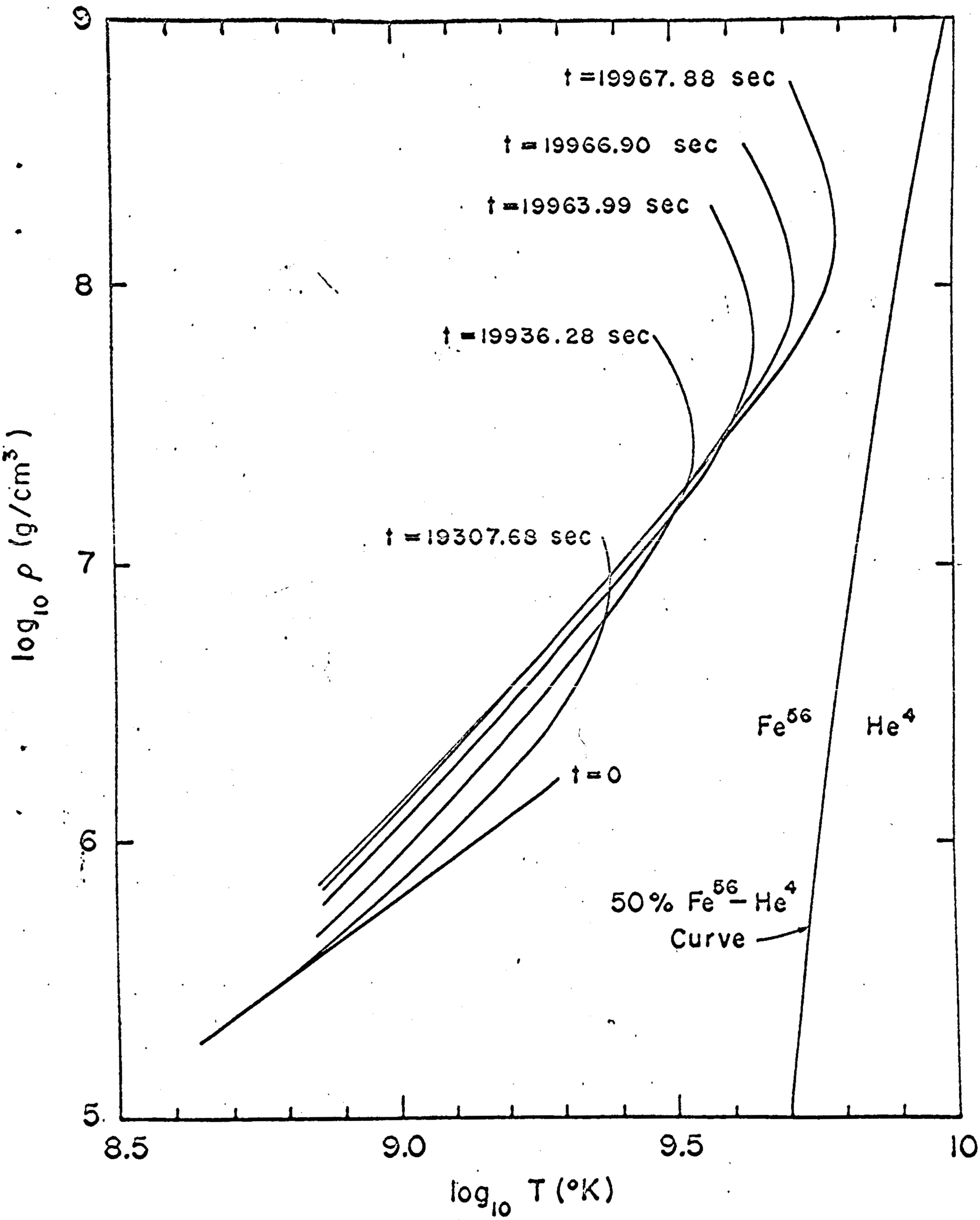
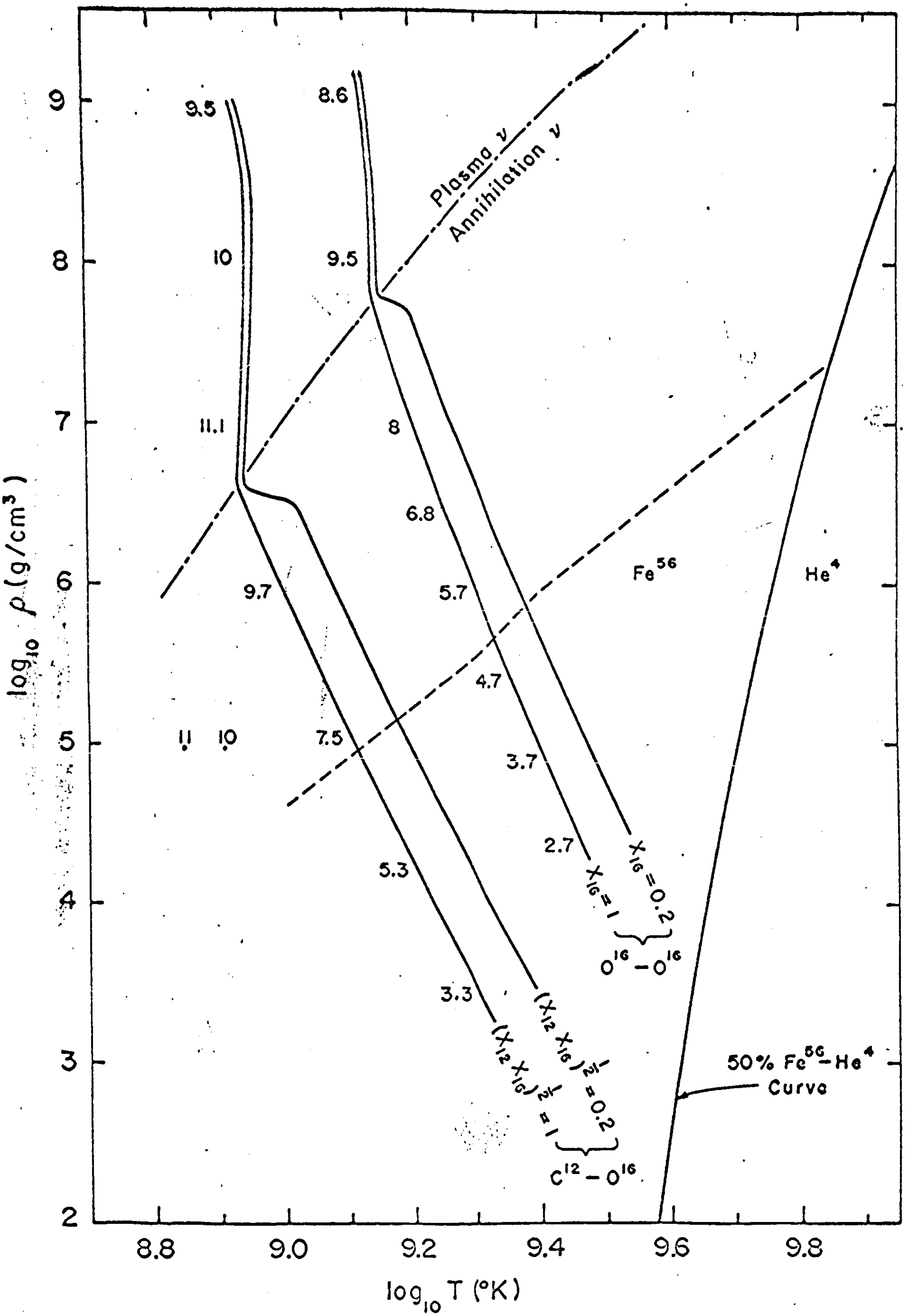

t = 19967.88 sec
t = 19966.90 sec
t = 19963.99 sec
t = 19936.28 sec
t = 19307.68 sec
t = 0
Fe^{56}
He^{4}
50% Fe^{56} – He^{4}
Curve
9
8
7
6
5
8.5
9.0
9.5
10
$\log_{10} \rho$ (g/cm^3)
$\log_{10} T$ (°K)

Figure 3.



Plasma ν
Annihilation ν
9.5
10
11.1
9.7
7.5
5.3
3.3
8.6
9.5
8
6.8
5.7
4.7
3.7
2.7
11
10
$X_{16}=1$
$X_{16}=0.2$
$O^{16}-O^{16}$
$(X_{12}X_{16})^{1/2}=1$
$(X_{12}X_{16})^{1/2}=0.2$
$C^{12}-O^{16}$
Fe^{56}
He^4
50% $Fe^{56}-He^4$
Curve
$\log_{10} \rho\,(g/cm^3)$
$\log_{10} T\,(°K)$
9
8
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